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**A 100 KW EXPERIMENTAL WIND TURBINE: SIMULATION OF
STARTING, OVERSPEED, AND SHUTDOWN CHARACTERISTICS**

by Leonard J. Gilbert
Lewis Research Center
Cleveland, Ohio 44135



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16. Abstract <p>The ERDA/NASA 100 kW experimental wind turbine designed and built near Sandusky, Ohio, by NASA-Lewis Research Center has been modeled on a digital computer in order to study the performance of a wind turbine under operating conditions. Simulation studies of starting, overspeed and shutdown performance have been made. From these studies operating procedures, precautions, and limitations have been prescribed.</p>					
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A 100 KW EXPERIMENTAL WIND TURBINE: SIMULATION OF STARTING, OVERSPEED, AND SHUTDOWN CHARACTERISTICS

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SUMMARY

As part of the national wind energy program under the direction of ERDA, the NASA Lewis Research Center has designed and built a large experimental wind turbine near Sandusky, Ohio. This wind turbine is a horizontal-axis, propeller-type machine with a two-bladed 125-foot rotor. It is designed to generate 100 kW power from a synchronous generator in an 18 mph wind. The system is intended to be used as a test bed for the evaluation of various wind turbine component designs for the national wind energy program.

The power system of the wind turbine has been simulated on a digital computer using a Continuous System Modeling Program (CSMP) on an IBM 360 Time Sharing System. Simulation studies of starting, overspeed, and shutdown performance have been made in order to anticipate the actual performance of the wind turbine. From these studies operating procedures, precautions, and limitations have been prescribed. This report describes the results of that analysis. The calculations showed that feathering the blades in an 18 mph wind can stop rotor rotation in 12 seconds, without causing unacceptably high blade root stresses.

INTRODUCTION

As part of the national wind energy program under the direction of ERDA, the NASA Lewis Research Center (LeRC) has designed and constructed a 100 kW wind turbine at the Plum Brook Station of LeRC near Sandusky, Ohio. The objective of this experimental wind turbine project is to provide, as soon as possible, engineering data for use as a base

for the entire wind energy program and to serve as a test bed for components and subsystems. This project and its status are described in published reports (refs. 1, 2, 3, and 4).

In order to predict and analyze performance of the wind turbine, a system model designed for a digital computer has been developed. The model facilitates analysis of both transient and steady-state performance of the system for varied parameters and operating conditions. Among the initial problems considered in the analysis of the turbine performance are those involving starting, overspeeding, and shutdown. The results obtained from studying these three areas with the computer model are discussed in this report.

ANALYSIS

System Description

The Lewis Research Center wind turbine is a horizontal-axis, propeller-type machine. A two-bladed, 125-foot diameter rotor, mounted on a 100 foot truss tower, drives a 125 kVA synchronous alternator through a conventional step-up gear box. The rotor is downwind of the tower and rotates at a constant speed of 40 rpm. The alternator operates at 1800 rpm and provides 60 Hz three-phase power. The system is rated at 100 kW in an 18 mph wind. Figure 1 is a sketch of the wind turbine. The details of the drive train assembly and the yaw system are shown in fig. 2.

Computer Model

In order to predict the starting, overspeed, and shutdown characteristics of the system, a computer model of the wind turbine was used. The computer simulation provides a means of calculating the time-dependent behavior of the wind turbine during rotor accelerations and decelerations resulting from aerodynamic and inertial forces. In the model, the system is partitioned into three subsystems: The rotor, the torque load, and the pitch control. These subsystems are depicted in fig. 3.

Rotor. - The usable torque, T_{in} , developed at the rotor shaft is a

function of wind velocity, V_w , blade pitch θ , and rotational velocity, Ω :

$$T_{in} = f(V_w, \theta, \Omega)$$

Torque load. - The torque load on the rotor represents the system inertial and damping torques as well as the torques produced by the alternator electrical load and system losses. Thus the torque balance of the system can be expressed by a differential equation equating the torque developed by the rotor to the sum of the torque loads. This gives:

$$T_{in} = J_{eq} \dot{\Omega} + B_{eq} \Omega + NT_L + L \quad (1)$$

where,

- J_{eq} inertia of the complete rotating system
- B_{eq} damping coefficient of the complete rotating system
- T_L torque load of alternator
- N gear ratio between high and low speed shaft
- L torque losses of system
- Ω rotor rotational speed
- $\dot{\Omega}$ rate of change of rotor rotational speed with time

Pitch control. - The rotational speed of the turbine is controlled by varying the pitch of the rotor blades. The pitch control is effected by a hydraulically powered control which varies the blade pitch in accordance with a feedback signal from the output shaft. The controller used for pitch control of the 100 kW wind turbine provides a proportional plus integral output signal in response to an input. The model assumed for the pitch control is described by the operational equation:

$$\theta(s) = \left(K_1 + \frac{K_2}{s} \right) \left(\frac{1}{\tau_p s + 1} \right) \Omega_e(s) \quad (2)$$

where

- s Laplace operator
- $\theta(s)$ pitch angle of blade

τ_p control hydraulic actuator time constant

$\Omega_e(s)$ rotor rotational speed error

K_1 controller proportional gain

K_2 controller integral gain

The control subsystem gains used for the analyses were $K_1 = 5.0$ and $K_2 = 0.5$. These values were determined by the computer study undertaken to determine gain values for satisfactory transient response of the wind turbine to wind gusts. They are the controller gains used in the wind turbine.

The dynamic response of the hydraulic subsystem was represented by the factor $\frac{1}{\tau_p s + 1}$ in equation (2), where $\tau_p = 0.1$ second. This value was considered to be representative of the actual hardwares used in the system.

Computer Program

To facilitate the analysis of this system on a digital computer, the IBM System/360 Continuous System Modeling Program (CSMP) was used. CSMP readily handles nonlinear and time-variant sets of differential equations. Reference 5 describes CSMP.

The principal nonlinear feature of a wind turbine, as far as the useful output is concerned, is the torque developed by the rotor. This torque is a function of the blade pitch, wind velocity, and rotational speed as well as the blade configuration. To generate values of the wind turbine developed torque for varying input conditions, use has been made of a computer program developed by Wilson and Lissaman (ref. 6). This Fortran program, written at Oregon State University, calculates wind turbine performance relatively rapidly. It uses a Simpson's Rule/three pass method of numerical integration. The program has been modified to return only that output pertinent to the studies described herein, and the computer time has been reduced appreciably. For a given propeller

geometry, this program calculates the torque developed by the propeller as a function of wind speed, rotor speed, and blade pitch.

RESULTS AND DISCUSSION

Starting

A set of torque-pitch characteristics of the 100 kW wind turbine is illustrated in fig. 4. This figure is a plot of the torque developed by the rotor as a function of the blade pitch angle for a 10 mph wind speed. Rotor rotational speed is the parameter. The blade pitch angle varies from -90° toward 0° , representing the change from a feathered condition to a power condition. Because the blade has twist, the pitch is referenced to the pitch at the $3/4$ radius point. In order to start rotation, it is necessary to "pitch-up" - that is, move the blade out of the feathered position. In the feathered position, no net lift is produced, and no torque is developed. As the blade is "pitched up", there is sufficient blade lift produced to rotate the propeller. As the rotational speed increases, and the blade pitch angle moves away from feather, the torque produced increases under certain conditions of pitch and speed. Since the torque increases only under these certain conditions, the rate at which the blade is "pitched up" is not arbitrary. Examination of fig. 4 will show that there are conditions of speed and angle for which the torque developed is negative. These conditions represent a deceleration of the rotor rather than an acceleration. Too rapid an angle change results in stalling the blades. Thus, a controlled pitch change program for starting is necessary.

One manner of programmed start is to vary the pitch at a fixed rate from the feathered position until a rotational speed of 40 mph (rated speed) is reached. When 40 rpm is reached, the fixed speed controller is actuated, providing closed loop speed control. A rapid pitch rate is desirable in order to avoid lingering at rotational speeds that excite system resonances. However, the pitch rate is limited by the rotor aerodynamic characteristics. Too rapid a pitch rate leads to blade stalling.

A parametric study was made to predict the time required for the 100 kW wind turbine rotor to accelerate from standstill to 40 rpm if the

blade pitch is advanced at a steady rate from the feathered position. Figure 5 shows the reduction in time to reach 40 rpm as the pitching rate is increased. The right hand termination of the curves occurs at the pitching rate at which the blades stall and the torque on the rotor would act to decrease rotor speed. Figure 3 shows time to reach 40 rpm for 2 wind speeds of 10 mph and 18 mph, these times vary from 158 seconds to 40 seconds respectively.

Another nonlinear feature of the wind turbine torque characteristics is indicated in fig. 6. As the wind speed increases from 10 to 18 mph, the startup time decreases with respect to the wind speed. This decrease in time occurs more rapidly at the lower wind speeds than at the higher wind speeds.

The variation of the startup rate with rotor inertia, J_{eq} , is shown in fig. 7. As expected the higher inertia rotor takes longer to reach 40 rpm, but the difference is relatively small at the higher wind speeds.

The acceleration of the rotor for this mode of constant pitching rate starting is significant because this acceleration increases rapidly as the rotational velocity increases. Figure 8 is indicative of the manner in which the rotor can be expected to accelerate for a pitch rate of $1^\circ/\text{sec}$ in an 18 mph wind velocity. The rotor torque producing this acceleration is shown in fig. 9.

Overspeed

Pitch control failure during operation of the wind turbine can result in excessive overspeeding of the rotor. The torques produced by the wind turbine in high wind and rotor overspeed conditions require a braking system to prevent excessive overspeed and possible rotor damage.

In order to predict the performance of the wind turbine in these critical circumstances, a severe failure mode was modeled on the computer and the system behavior was studied. It was assumed that the pitch control failed and the pitch remained fixed at the rated power condition as the wind speed increased. Specifically, the conditions assumed were a wind increasing in speed from rated speed of 18 mph to a speed of

36 mph at a 1mph/sec rate while the blades remained fixed and the system was carrying rated load. The objective of the investigation was to determine the braking torque required to prevent the rotor from accelerating to destructive speeds. To simulate the brake a step load torque was applied to the system.

For the assumed conditions, if the torque load (braking torque) is not large enough, the rotor will rapidly accelerate to high speeds. This performance is illustrated in fig. 10. For the problem illustrated, the rated load was 21,400 lb-ft at rated speed. As the wind speed increased (with a fixed pitched propeller), the rotor speed increased. When the speed reached 45 rpm, a simulated braking torque was applied to the output shaft. A braking torque of 3 times rated (64,200 lb-ft) was not adequate to stop the acceleration (fig. 10). A torque of 3.5 times rated (74,900 lb-ft) was required to stall the blades and bring the rotation to a halt. As the brake is applied and the rotational speed decreases, the blades stall because the blade pitch angle is too flat for the slower speed. The inertial energy of the rotor at the time the brake is applied must be absorbed by the brake and its surroundings. In the example shown this energy is 1.11×10^6 ft-lbs. This response is illustrated in fig. 10. The changing torque produced in each instance is shown in fig. 11. Yawing the rotor out of the wind, that is, orienting the rotor so that the wind velocity is not perpendicular to the plane of rotation of the blades, is also a means of rotor speed control. However, yawing the 100 KW research wind turbine is not an effective means of preventing overspeed in the event of a blade pitch failure because the yawing rate available ($1^\circ/\text{sec}$) is limited. The changing torque-producing component of the wind velocity as the rotor is yawed is indicated in fig. 12. There was virtually no effect on the rotor speed performance when a yawing procedure was included in the simulation.

Emergency Shutdown

In emergency conditions, the rotor blades are feathered (or pitched to the no-power position) at a constant rate of $8^\circ/\text{sec}$.

This action produces reverse thrust on the rotor and higher than usual blade root moments. This rapid feathering was simulated to predict the rotor response. The rotor performance shown in the computer traces of fig. 13 is for the rapid feathering action from an operating condition of 40 rpm, no load, in a 24 mph wind.

The rotor speed decreases as shown in fig. 13(a) as the blade pitch moves toward feather at the fixed rate illustrated in fig. 13(b). As a result of the increased pitch, the rotor develops the negative torque (fig. 13(c)) which decelerates the rotor. The rapid slowing of the rotor produces a corresponding negative thrust shown in fig. 13(d).

To summarize, these calculations have shown that the rapid feathering can shut the rotor down in less than 12 seconds. Further, although the blade root loads for this condition are higher than usual, they are still within the design load case limits.

CONCLUDING REMARKS

The 100 kW wind turbine designed and built by NASA LeRC near Sandusky, Ohio, has been modeled on a digital computer in order to study the performance of this kind of power system under operating conditions. Simulation calculations of starting, overspeed, and shutdown have shown the highly nonlinear characteristics of the wind turbine developed torque. The following specific information has been determined from the simulation calculations:

1. The wind turbine 'pitch up' - the rate of pitching the blades toward the maximum power position - must be controlled and limited during starting to avoid stalling the blades.
2. The braking torque required to stall the rotor under conditions of a fixed blade pitch and an increasing wind speed is critical. For this particular 100 kW wind turbine it must be at least 3.5 times rated torque.
3. Rapid feathering of the blades for an emergency shutdown results in stopping the rotor in less than 12 seconds when operating initially at 40 rpm in a wind speed of 24 mph. This condition produces the maximum loads on blade roots, but these loads do not exceed the allowable blade design loads.

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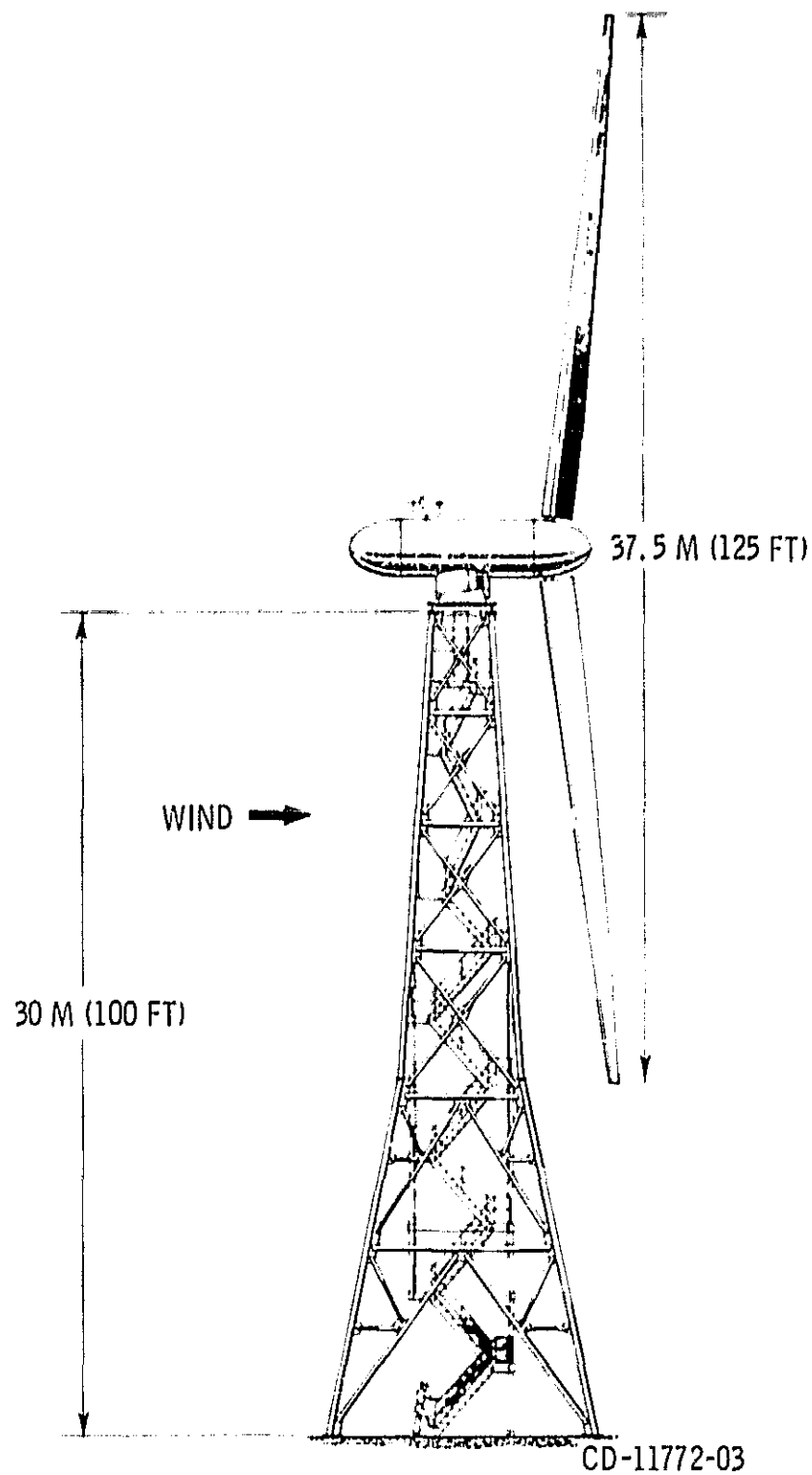
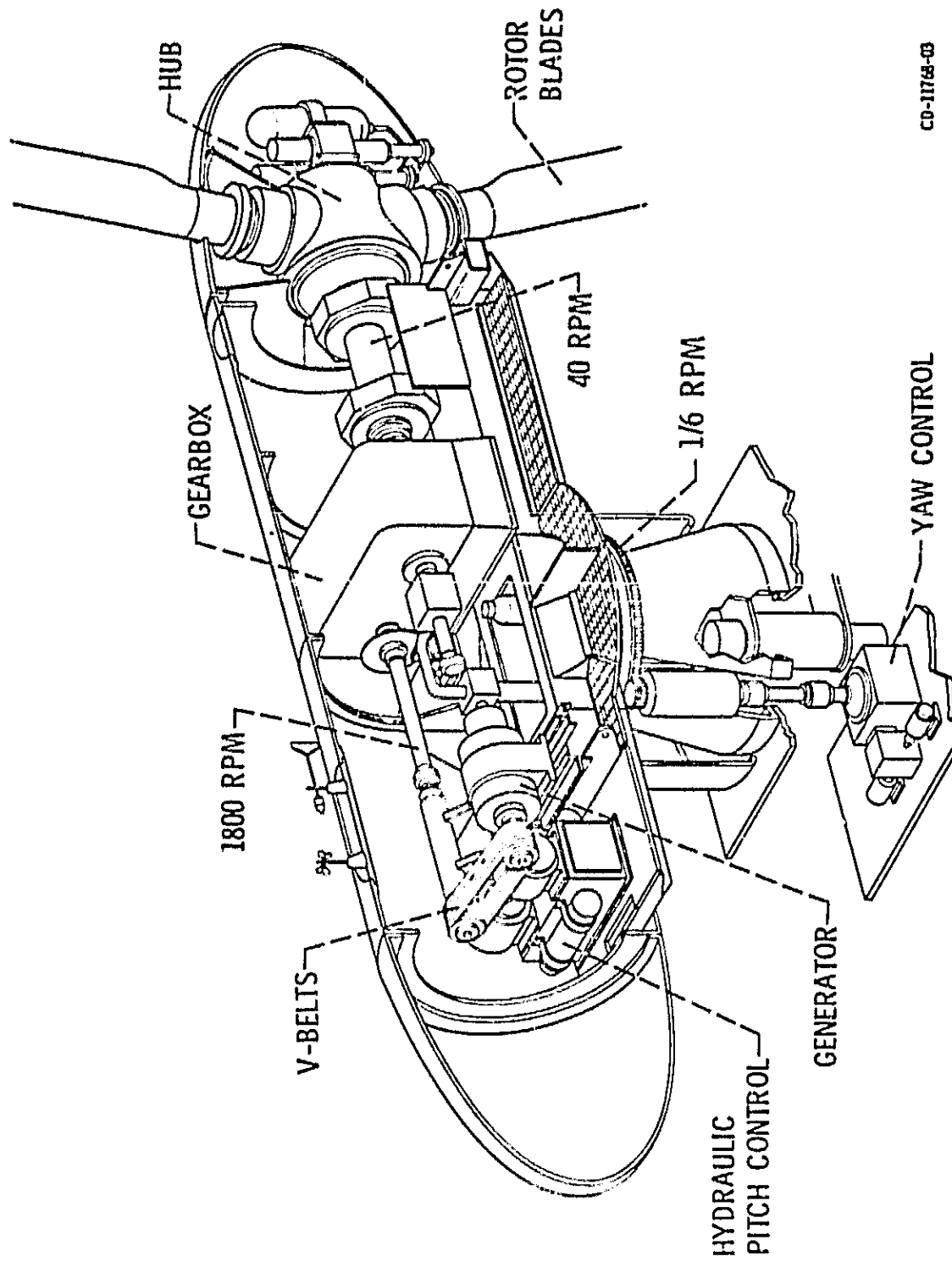


Figure 1. - 100-kilowatt experimental wind turbine.

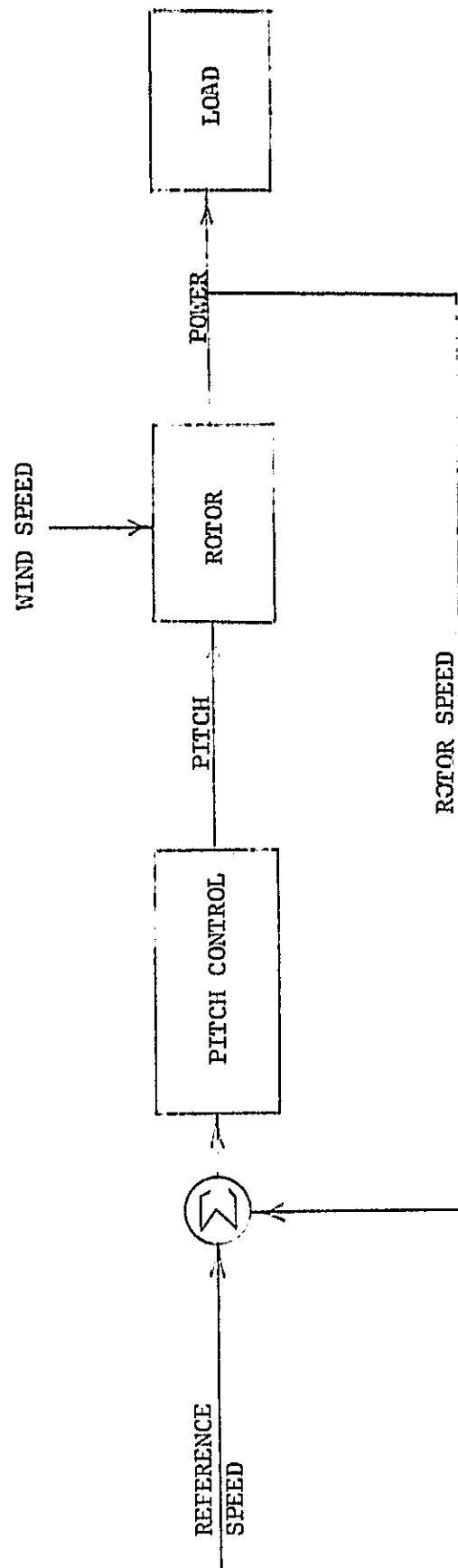
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100 KW EXPERIMENTAL WTG
100 KW WIND TURBINE DRIVE TRAIN ASSEMBLY



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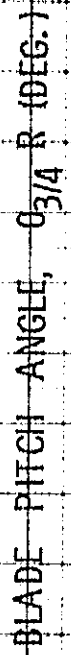
FIGURE 2



BASIC SIMULATION MODEL

FIGURE 3

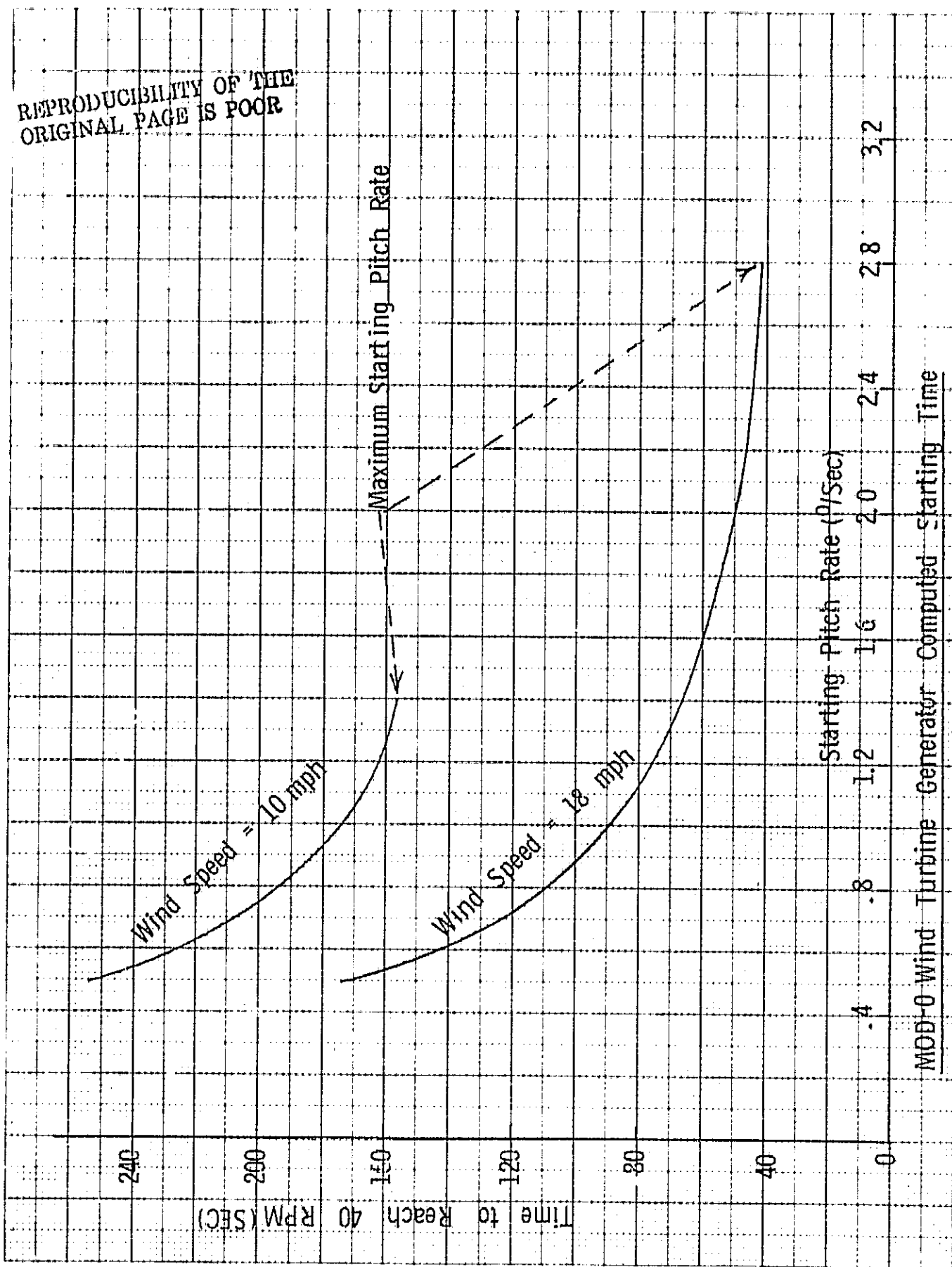
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ROTOR SPEED = 0 to 40 rpm

Figure 4

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MOD-0 Wind Turbine Generator Computed Starting Time

Figure 5

